Fast Oscillation Waves in Dense Neutrino Gases

Huaiyu Duan

Topics in Cosmic Neutrino Physics

October 9 — 11, 2019, Fermilab

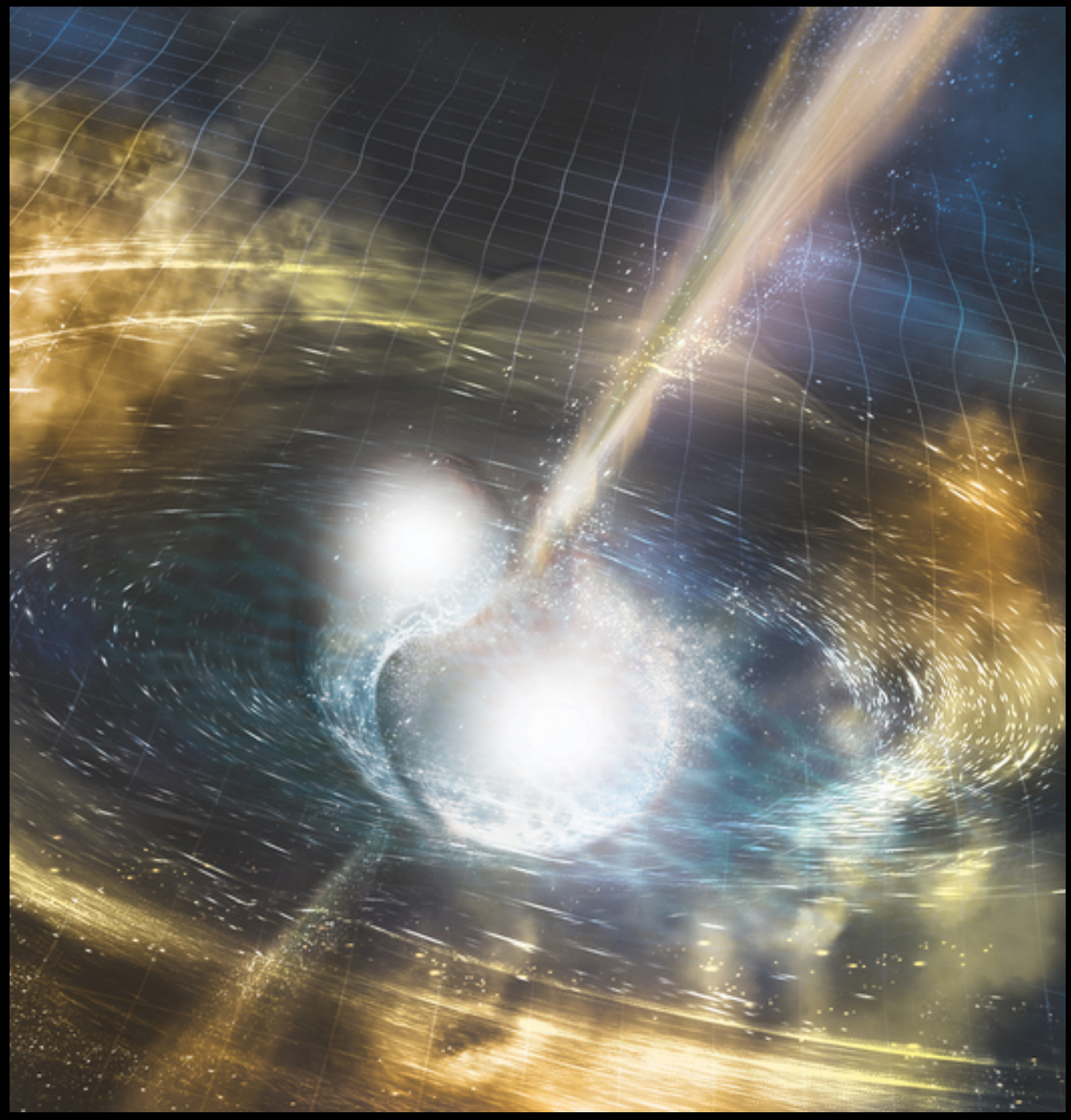
U.S. DEPARTMENT OF ENERGY | Office of Science

THE UNIVERSITY OF NEW MEXICO

Supernova

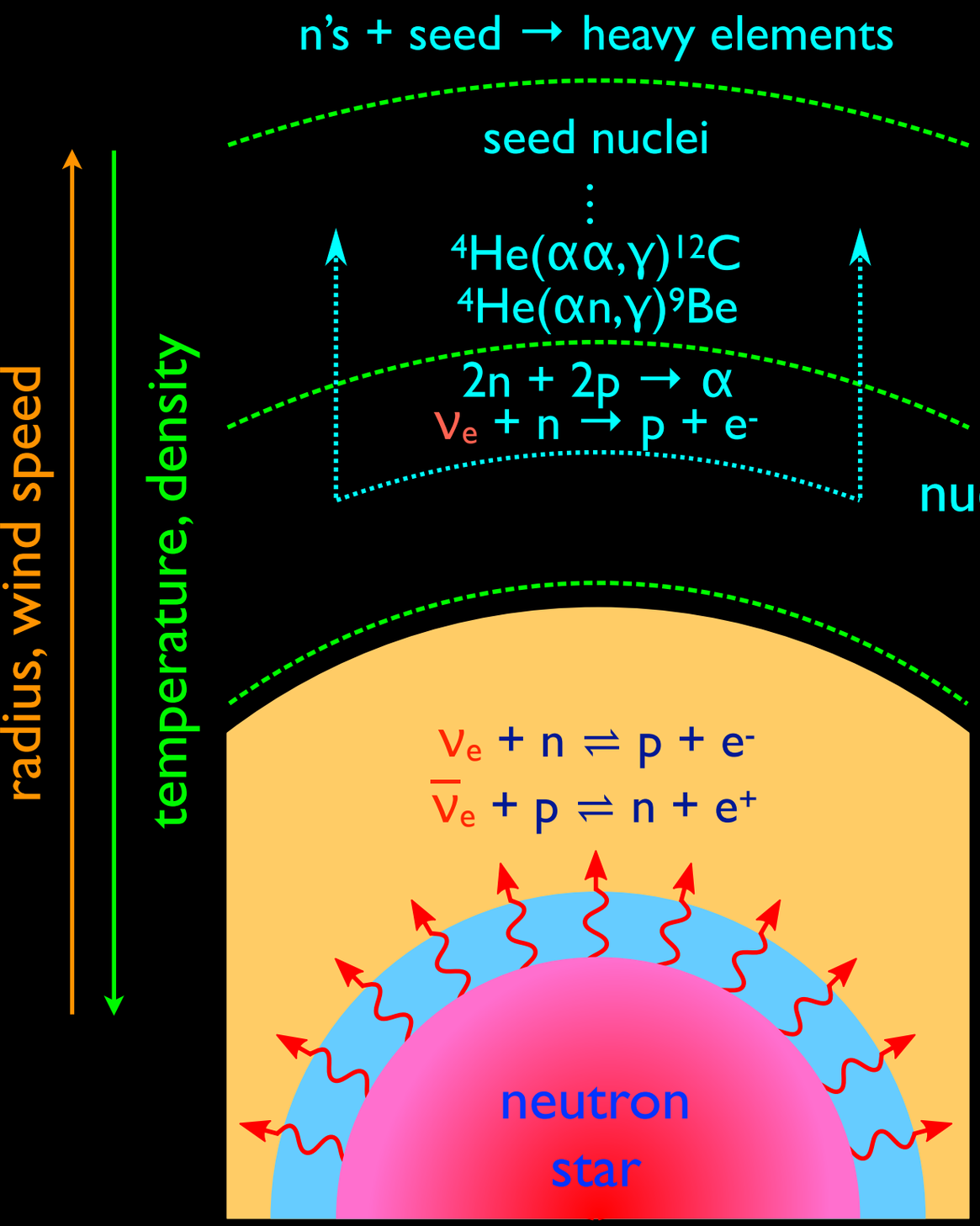
David Malin / AAO

Neutron Star Merger



NSF/LIGO/Sonoma State University/A. Simonnet

Neutrino in SNe



r-process
T≈0.25MeV

T≈0.75MeV
nucleosynthesis

WFO
T≈0.9MeV

heating region

cooling region

- ~10^{53} ergs, 10^{58} neutrinos in ~10 seconds
- All neutrino species, 10~30 MeV
- Dominate energetics
- Influence nucleosynthesis
- Probe into SNe

Oscillations in Dense Media

$$(\partial_t + \hat{\mathbf{v}} \cdot \boldsymbol{\nabla})\rho = -\mathrm{i}[\mathsf{H},\, \rho] + \mathcal{C}$$

mass matrix

electron density

$$\mathsf{H} \quad = \quad \frac{\mathsf{M}^2}{2E} \quad + \quad \sqrt{2}G_{\mathrm{F}}\,\mathrm{diag}[n_e, 0, 0] \quad + \quad \mathsf{H}_{\nu\nu}$$

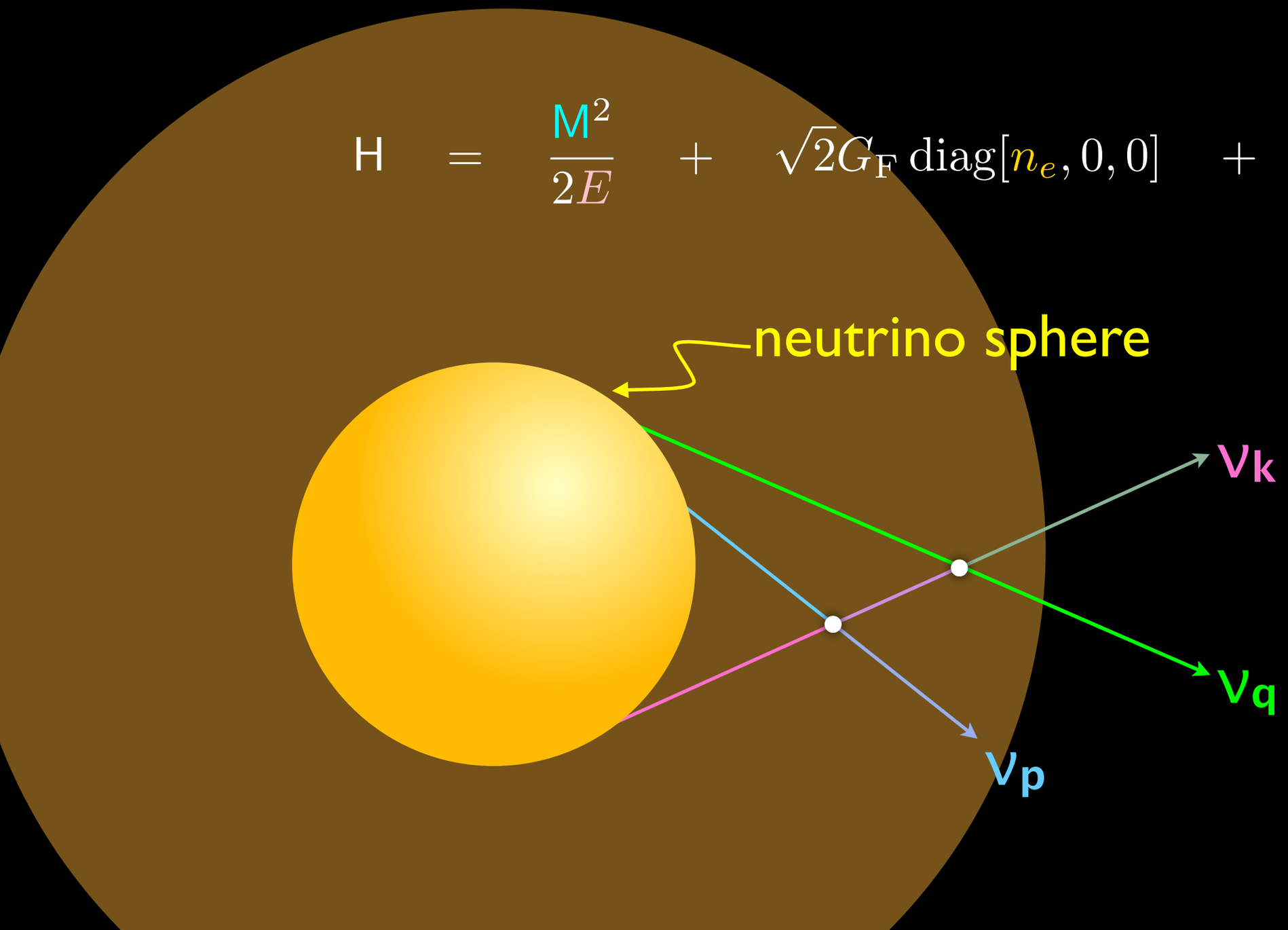
neutrino energy

ν–ν forward scattering
(self-coupling)

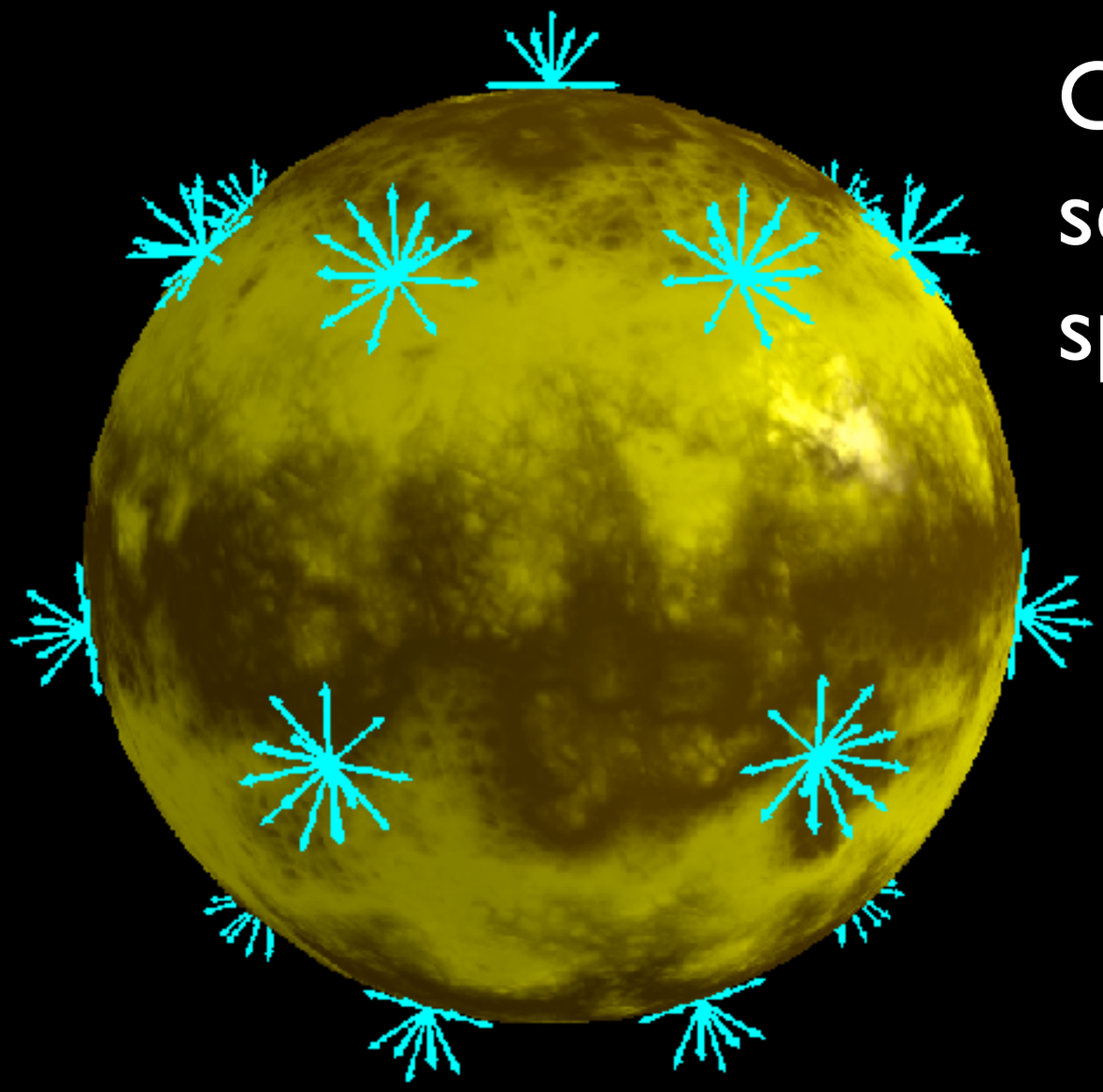
$$\mathsf{H}_{\nu\nu} = \sqrt{2}G_{\mathrm{F}} \int \mathrm{d}^3\mathbf{p}'(1 - \hat{\mathbf{v}} \cdot \hat{\mathbf{v}}')(\rho_{\mathbf{p}'} - \bar{\rho}_{\mathbf{p}'})$$

Oscillations in Dense Media

$$\mathsf{H} \quad = \quad \frac{\mathsf{M}^2}{2E} \quad + \quad \sqrt{2} G_{\mathrm{F}}\, \mathrm{diag}[n_e, 0, 0] \quad + \quad \mathsf{H}_{\nu\nu}$$



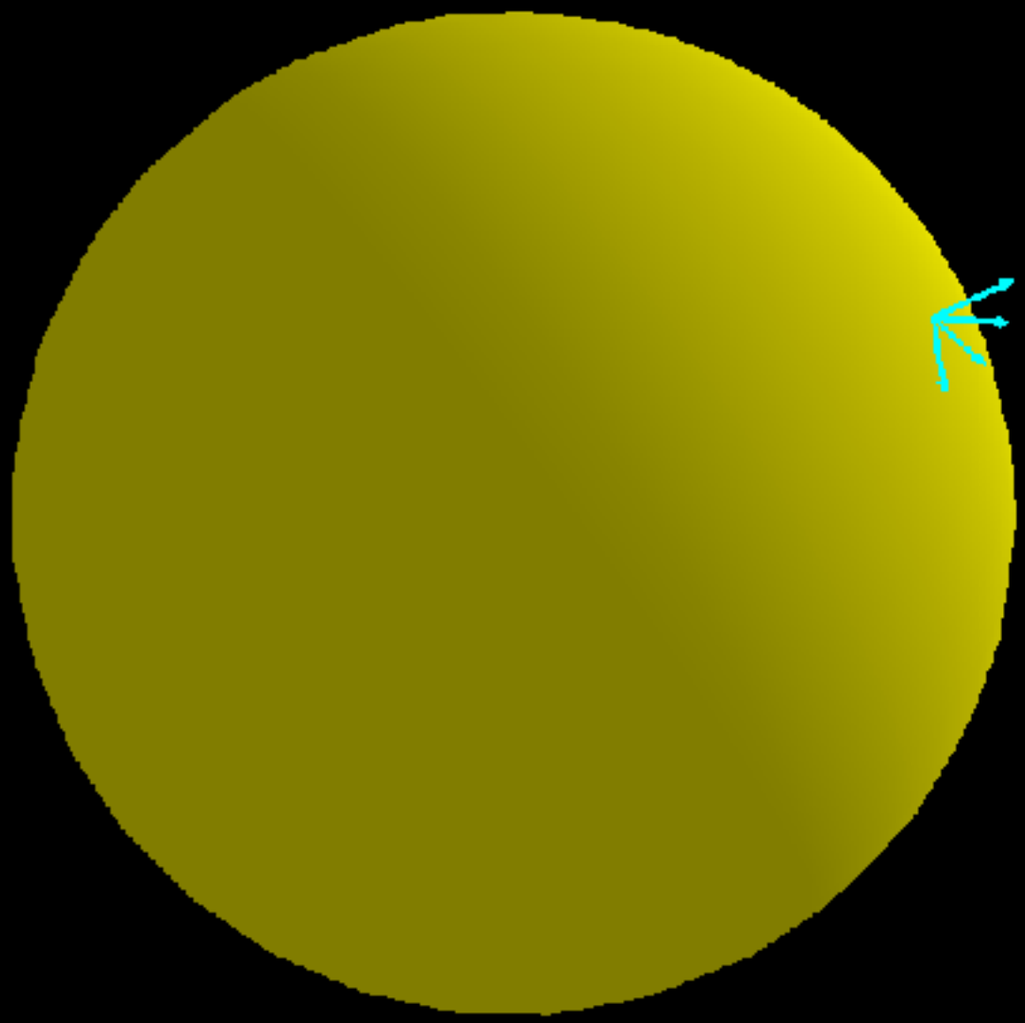
7D Problem



Coherent forward scattering outside neutrino sphere

$$\rho(t; r, \Theta, \Phi; E, \vartheta, \varphi)$$

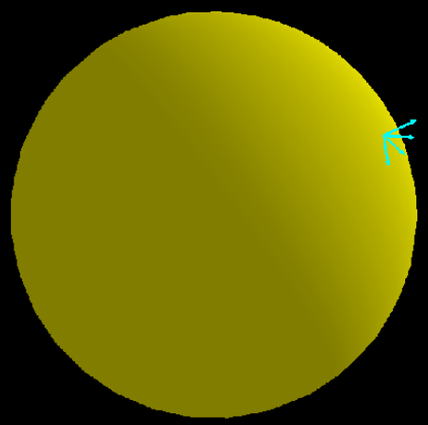
Bulb Model

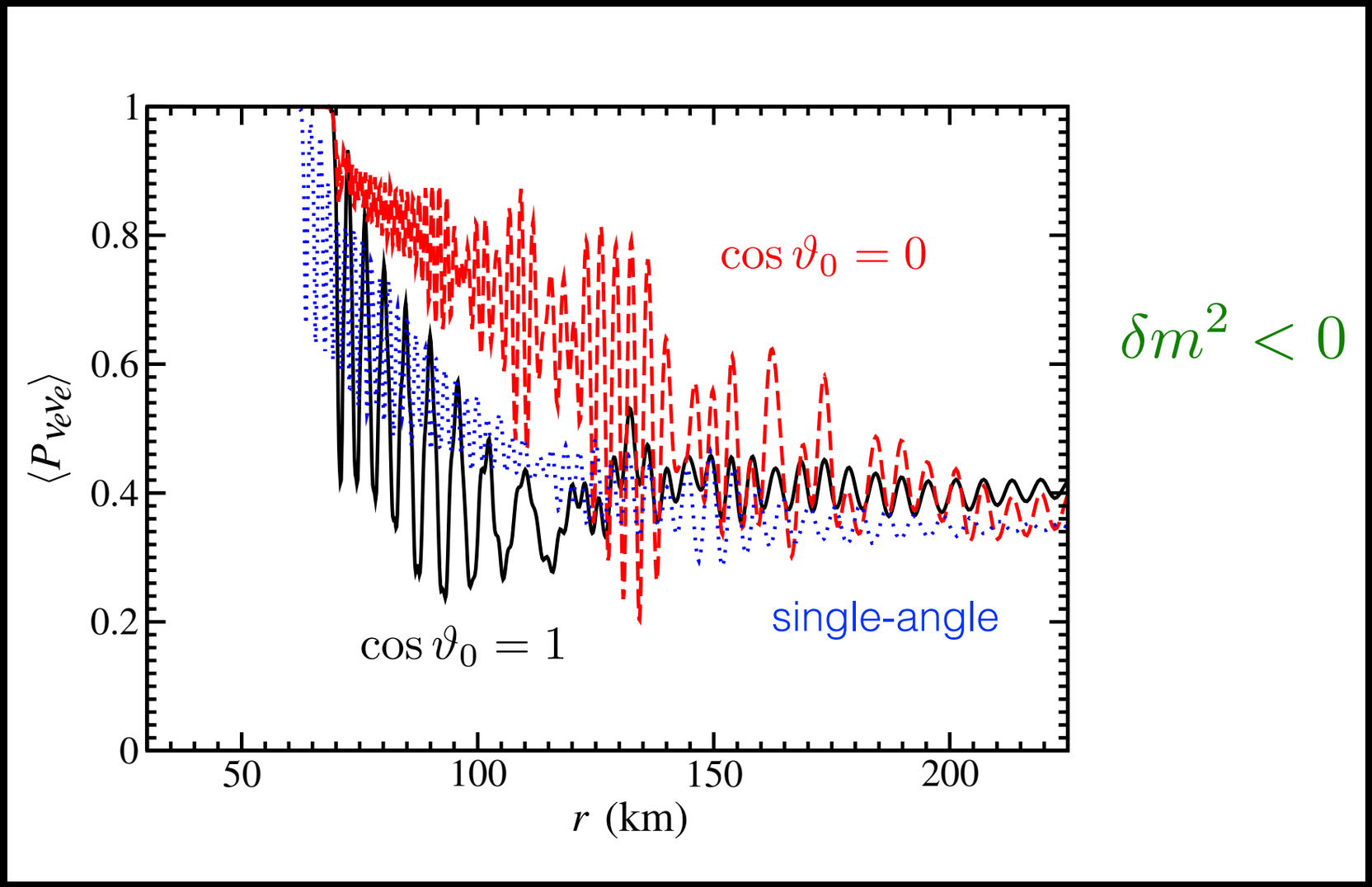


Azimuthal symmetry around any radial direction

$$\rho(r; E, \vartheta)$$

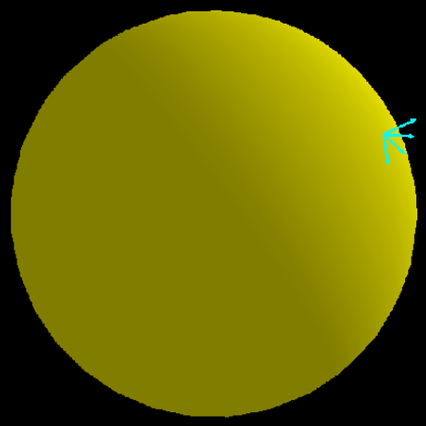
Bulb Model

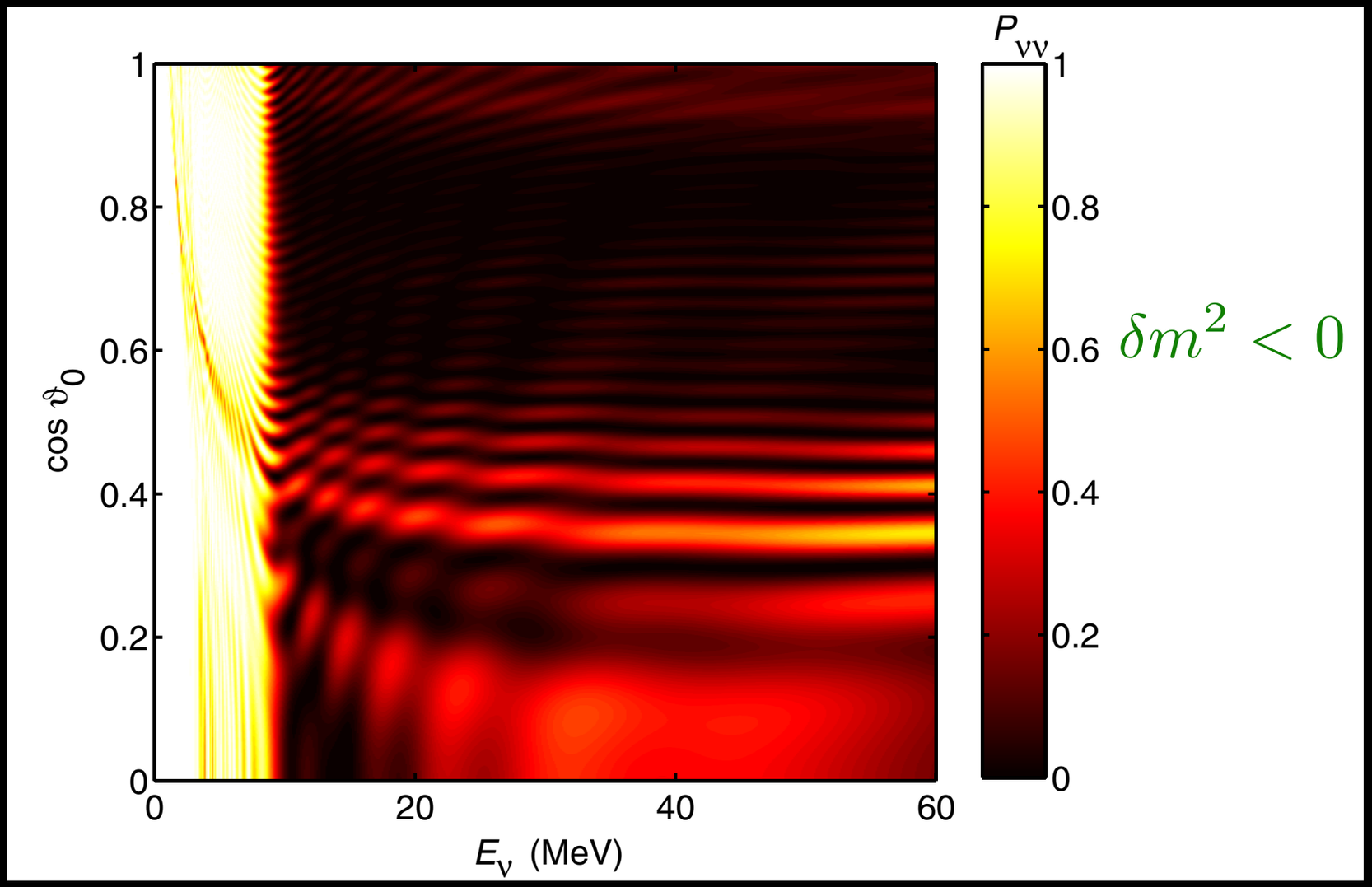




HD, Fuller, Carlson, Qian (2006)

Bulb Model





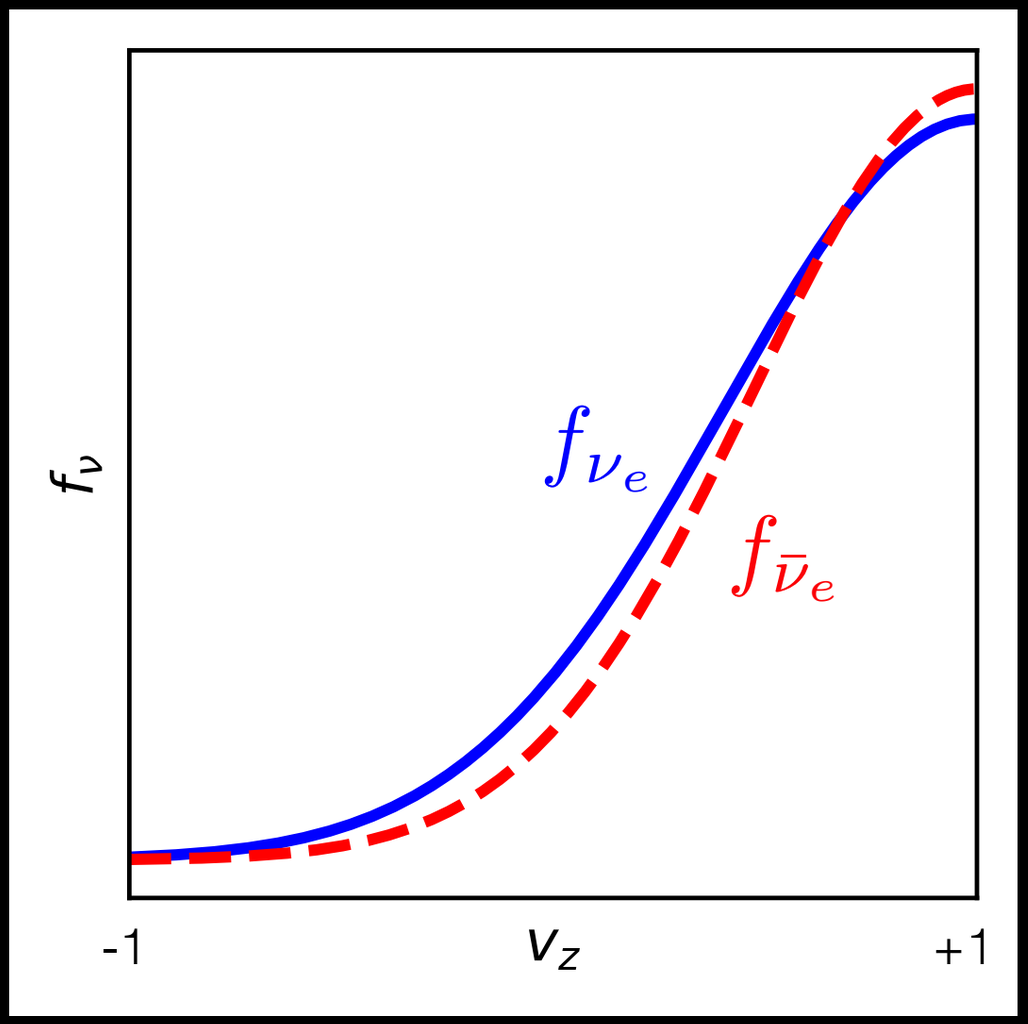
HD, Fuller, Carlson, Qian (2006)

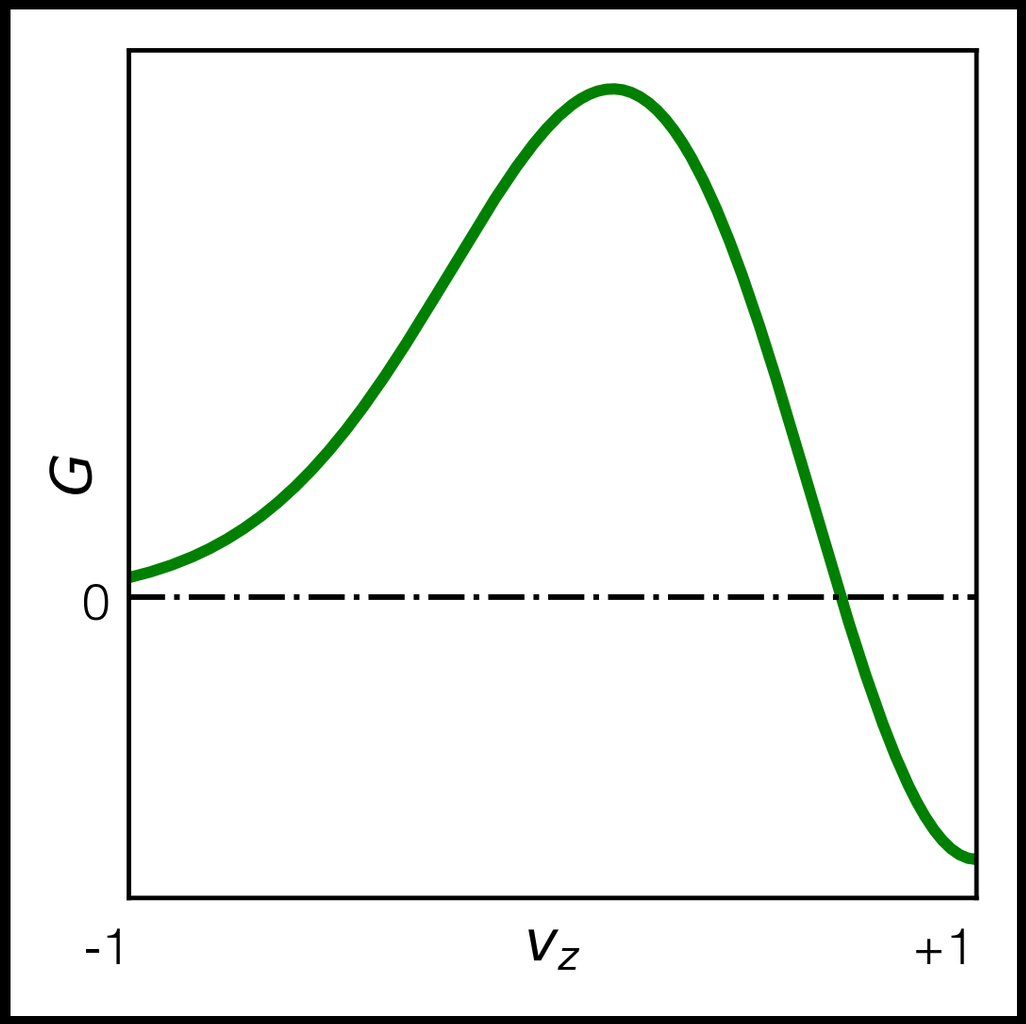
Fast Oscillations

- "Slow" oscillations occur on the distance scale of 1 km (~10 MeV / δm_{atm}^2).
- "Fast" oscillations can occur on the distance scale of 1 cm (~G_F n_ν), independent of the neutrino energies (Sawyer, 2016).
    - Requires crossed electron lepton number (ELN) distribution (Dasgupta et al, 2016).

ELN Crossing

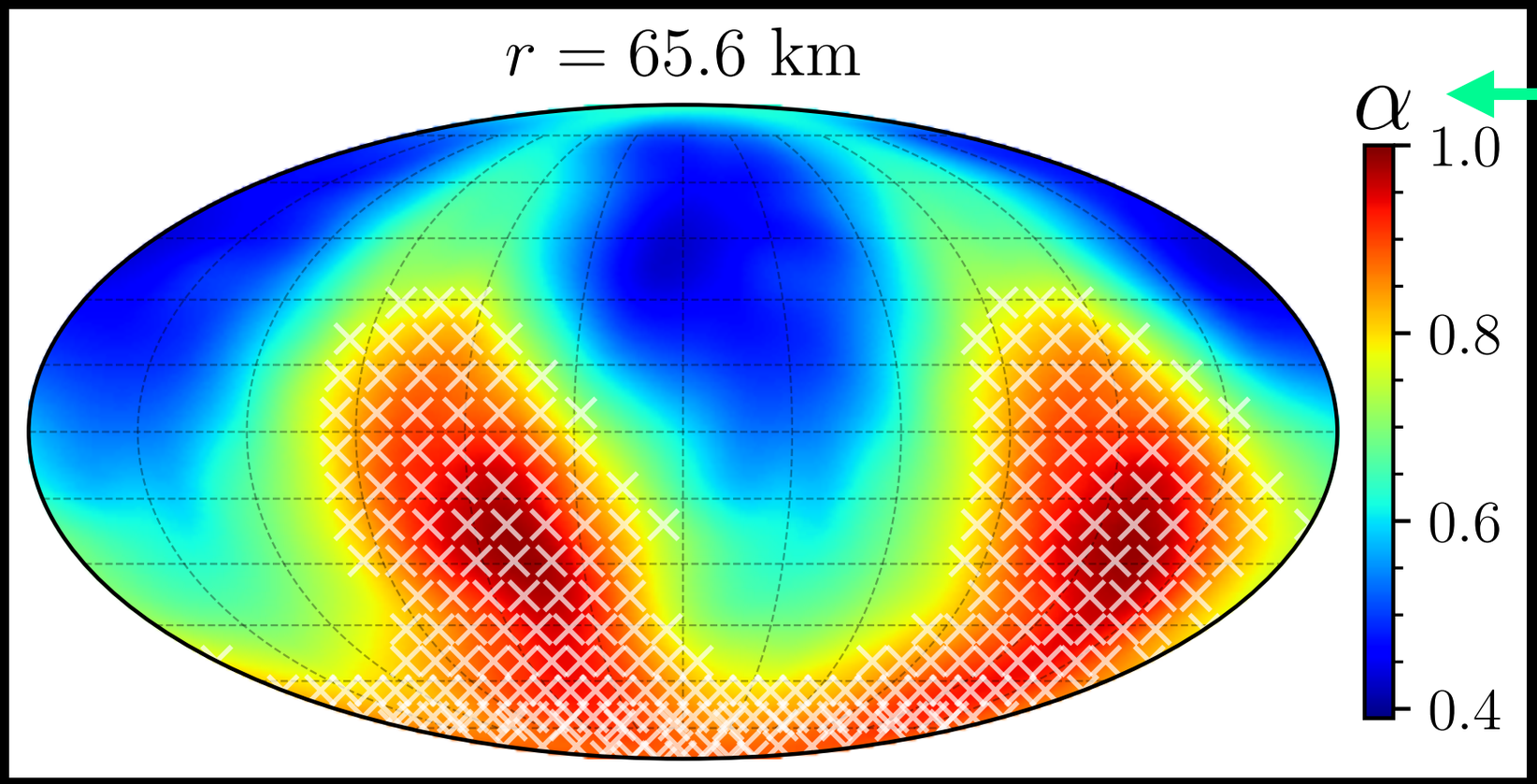
$$G = (f_{\nu_e} - f_{\bar{\nu}_e}) - (f_{\nu_x} - f_{\bar{\nu}_x})$$





ELN Crossing

11.2 $M_\odot$, t_{pb}=200ms, 3D ν transport (post-proc.)

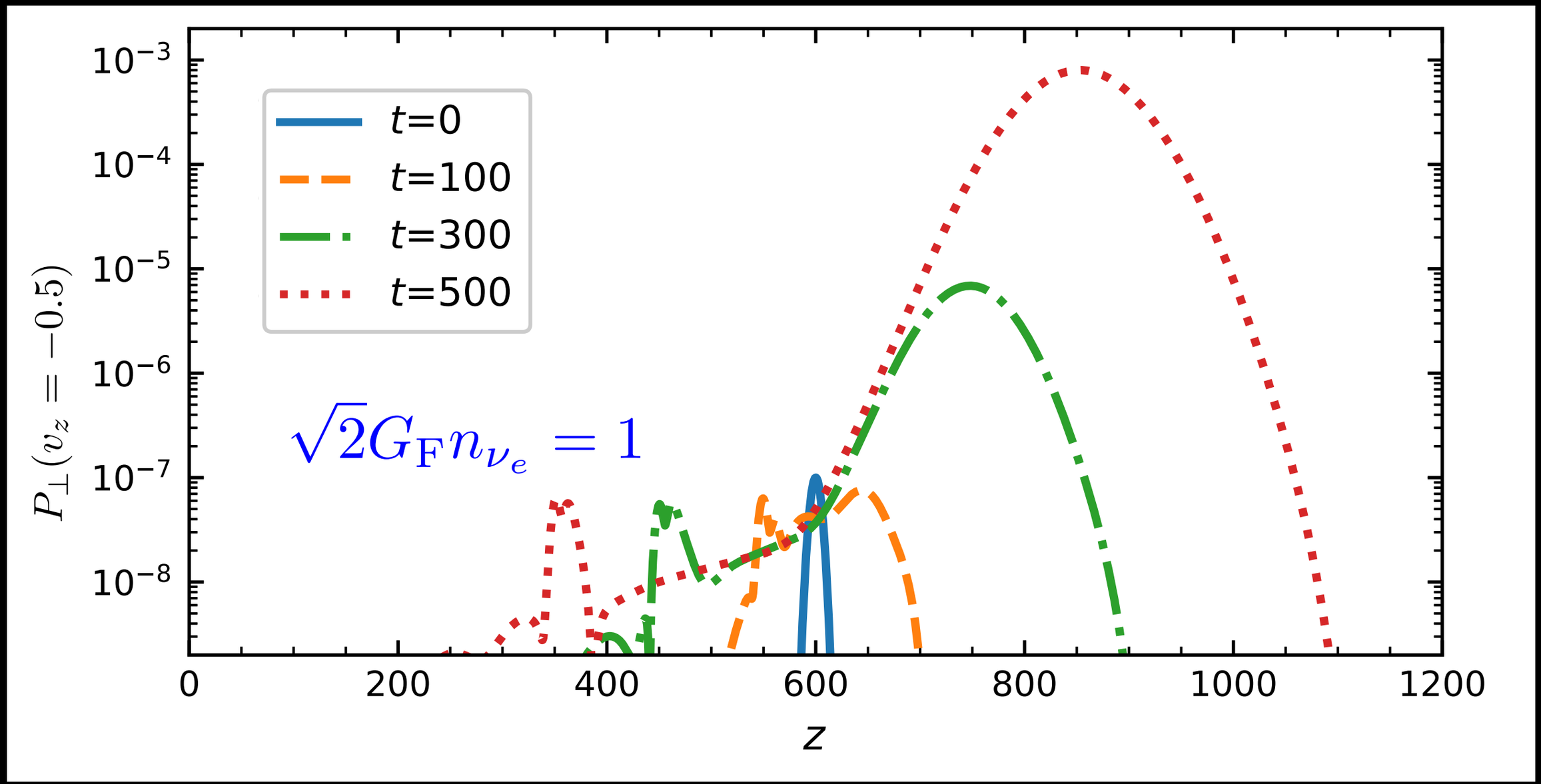


Abbar, HD, Sumiyoshi, Takiwaki & Volpe (2018)

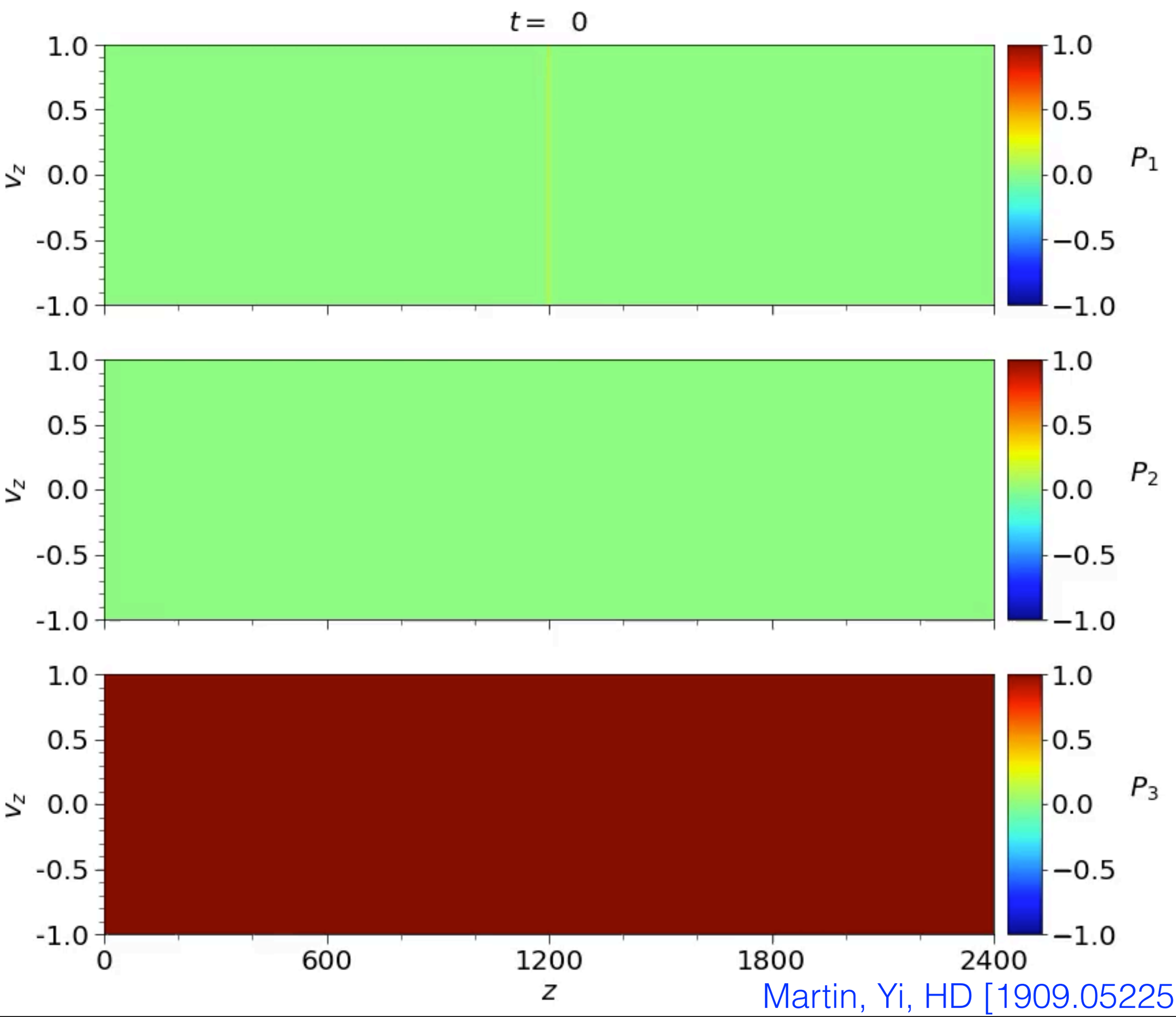
Fast oscillation growth rate dominates the collision rate (Capozzi et al, 2018)

Growing Perturbation

$$\rho(t,z,v_z) = \begin{bmatrix} n_{\nu_e} & \rho_{ex} \\ \rho_{ex}^* & n_{\nu_x} \end{bmatrix} \propto \begin{bmatrix} P_3 & P_1 - \mathrm{i}P_2 \\ P_1 + \mathrm{i}P_2 & -P_3 \end{bmatrix} + \text{t.t.}$$



Martin, Yi, HD [1909.05225]



Martin, Yi, HD [1909.05225]

Summary

- Flavor oscillation waves can propagate through the dense neutrino gases in core-collapse supernovae (SNe) and binary neutron mergers.

- “Fast” oscillations can occur on very short distance scales where ELN crossing occurs. (Need SN simulation inputs).

- Redistribution and transportation of ELN can have ramifications in SN physics (dynamics, nucleosynthesis, signals, …).